The Coherent Elastic Neutrino Nucleus Scattering (CENNS) Experiment at the Booster Neutrino Beamline

PHYSICAL REVIEW D **89,** 072004 (2014)

A method for measuring coherent elastic neutrino-nucleus scattering at a far off-axis high-energy neutrino beam target

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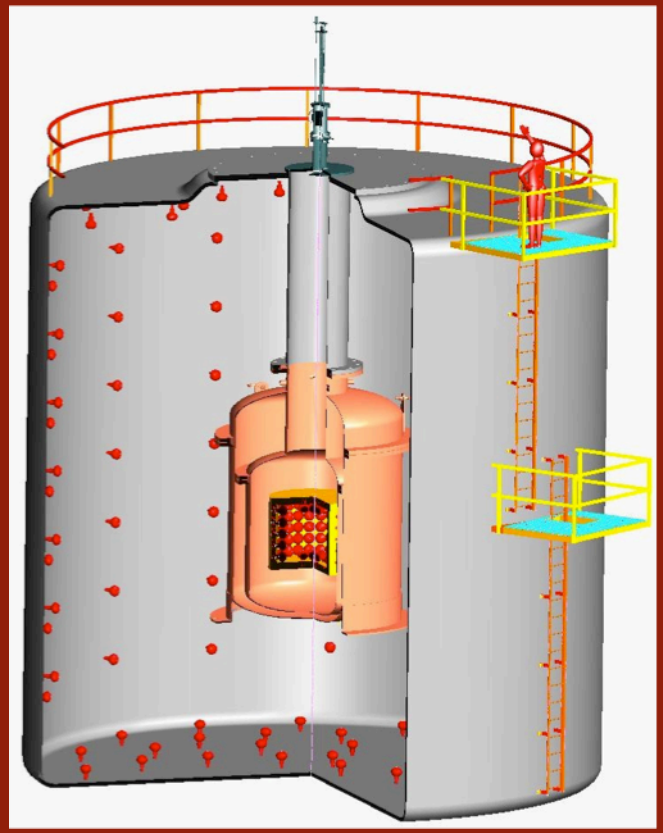

Robert Cooper

http://neutrino.indiana.edu/rlcooper

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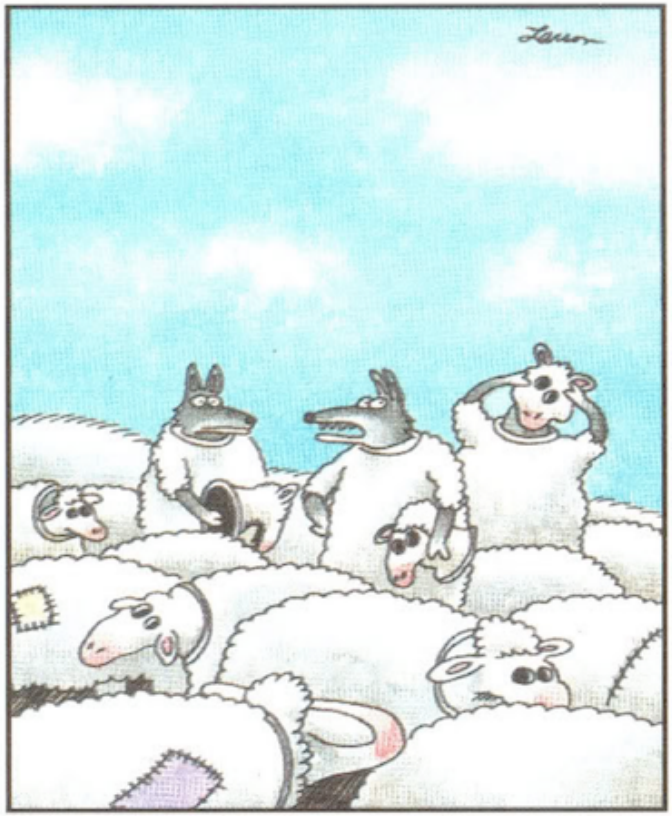
Outline

- Physics Motivation for CENNS
- How do we measure CENNS?
  i.) Neutrino production
  ii.) Detection
  iii.) **Background suppression**
- The SciBath Detector
- Future work and conclusions



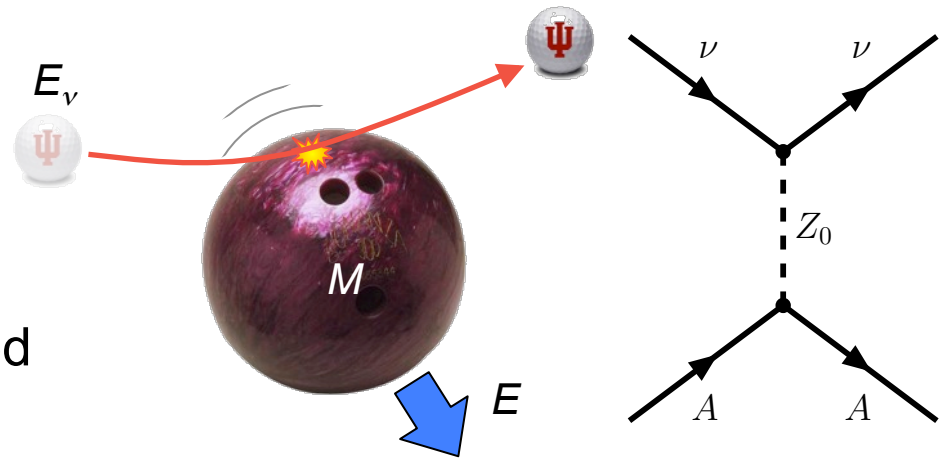
"Wait a minute! Isn't anyone here a real sheep?"

Describing the CENNS Signal

- To probe a “large” nucleus (few × 10^{-15} m)

$$E_\nu \lesssim \frac{hc}{R_N} \cong 50 \text{ MeV}$$

- Detector signature is the recoiling nucleus



- Recoil energy that is deposited

$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50 \text{ keV}$$

- This is quite small for particle & nuclear physics → Dark Matter

Structure of the CENNS Signal

- Predicted scattering rate

$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}\left[(1-4\sin^2\theta_w)Z - N\right]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)F(Q^2)^2$$

≈ 0 → protons have little influence

square of sum → part of coherence condition

nuclear form factor → distribution of neutrons

- Recoil energy (M^{-1}) and rate (N^2)

ν Cross Sections vs. Energy

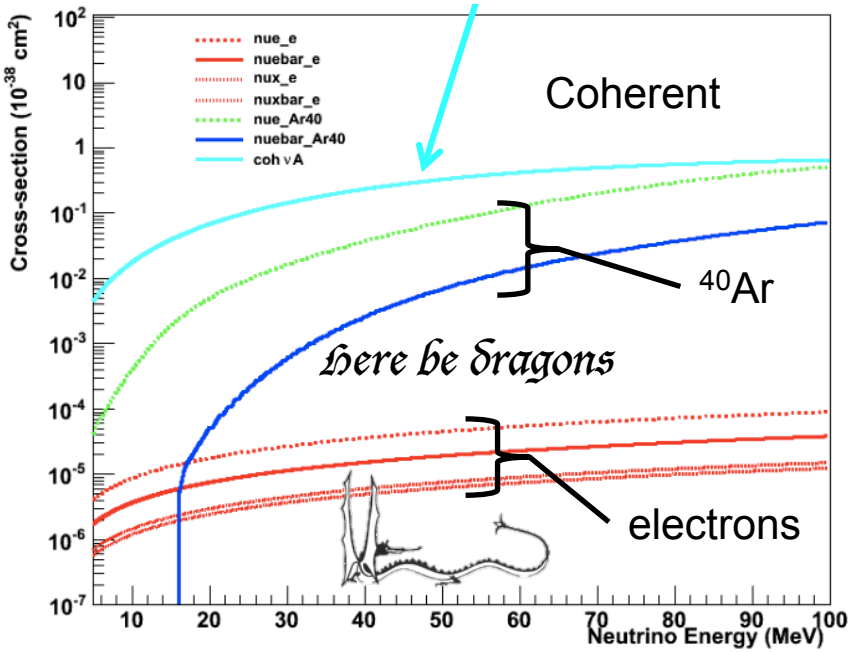


Image from K. Scholberg

Physics Cases for CENNS

- **Never been observed!**
- Oscillations (spatially)
- Form factors
- Supernova physics
- Non-standard interactions
- Irreducible dark matter background

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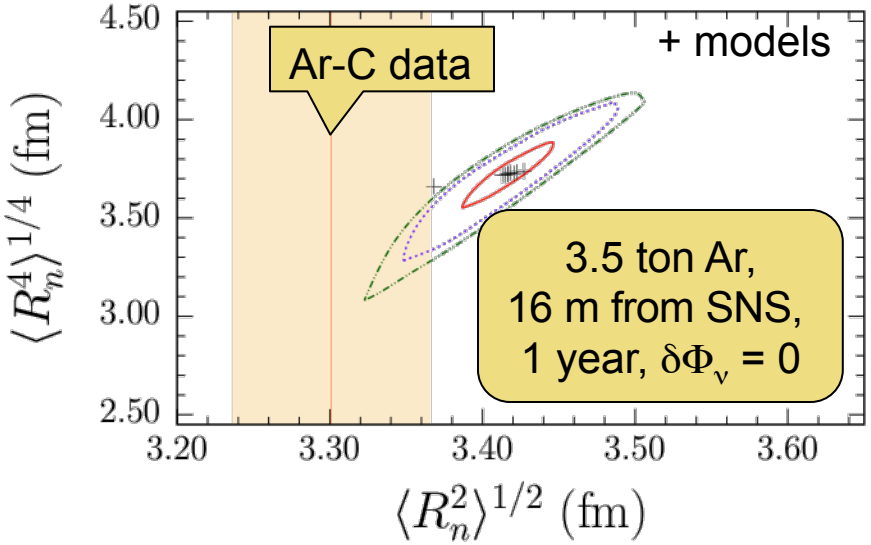
4th vs 2nd Form Factor Moments

$$F(Q^2) = \frac{1}{Q_W}\left[F_n(Q^2) - (1 - 4\sin^2\theta_W)F_p(Q^2)\right]$$

$$F_n(Q^2) \approx \int \rho_n(r)\left(1 - \frac{Q^2}{3!}r^2 + \frac{Q^4}{5!}r^4 - \frac{Q^6}{7!}r^6 + \cdots\right) r^2 dr$$



Patton et al., arXiv/1207.0693

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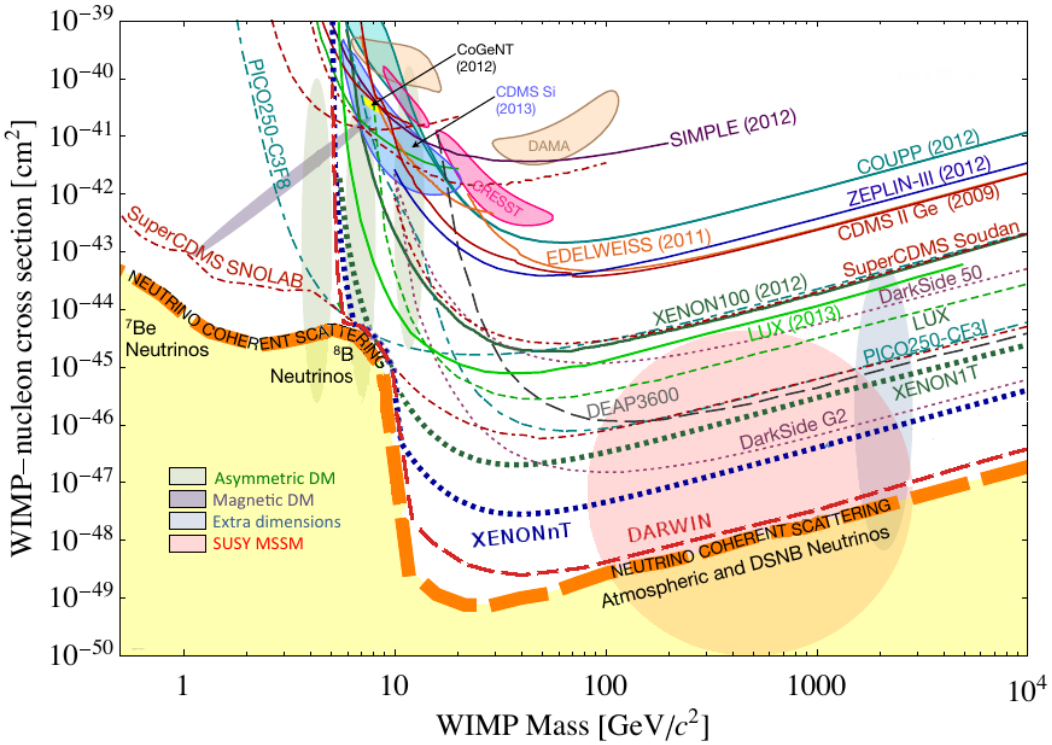
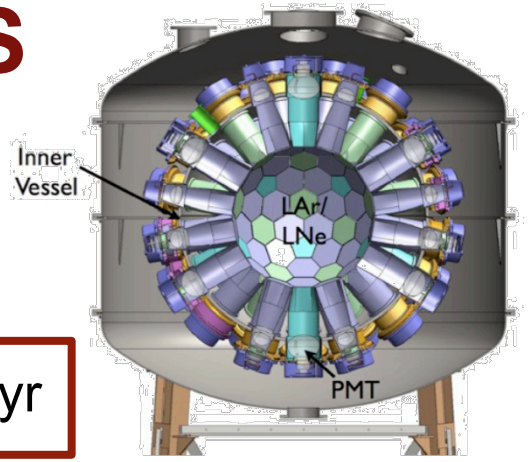
Dark Matter Sensitivity



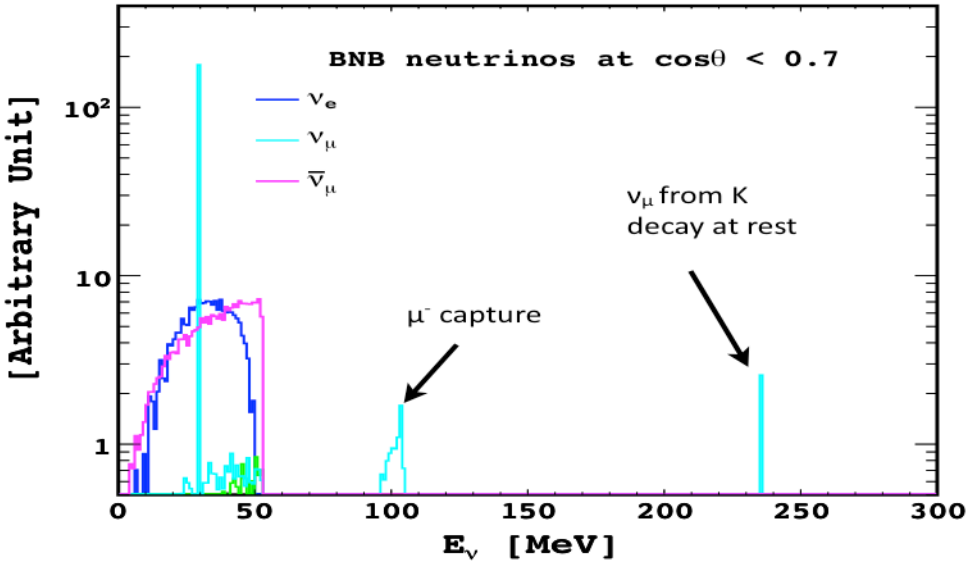
L. Baudis, Phys.Dark Univ. 4 (2014) 50-59 arXiv:1408.4371

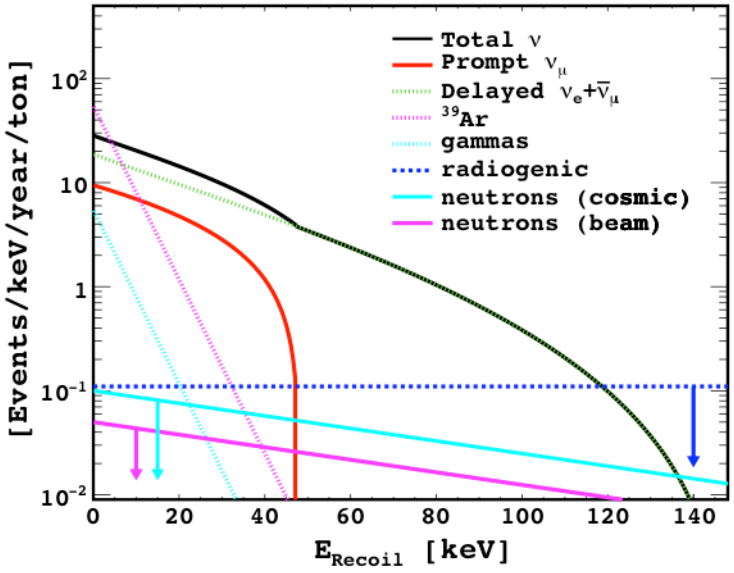
MiniCLEAN for BNB CENNS

- A. Hime already gave an excellent review of MiniCLEAN for BNB CENNS measurement



- ½ ton LAr scintillation detector → 100 events / yr

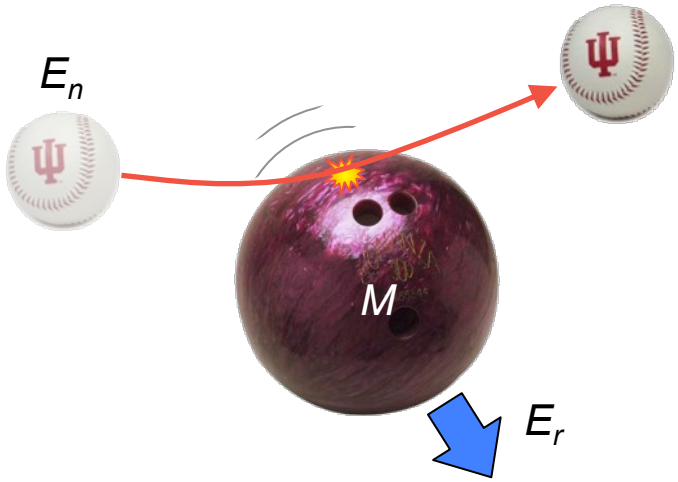




Neutron Backgrounds

- Few-MeV neutrons will deposit ~10 keV in LAr
- Accelerator produces all energies up to 8 GeV
- Shielding is needed
- Beam-correlated neutrons mimic neutrino signal

Neutron Scatter on ^{40}Ar

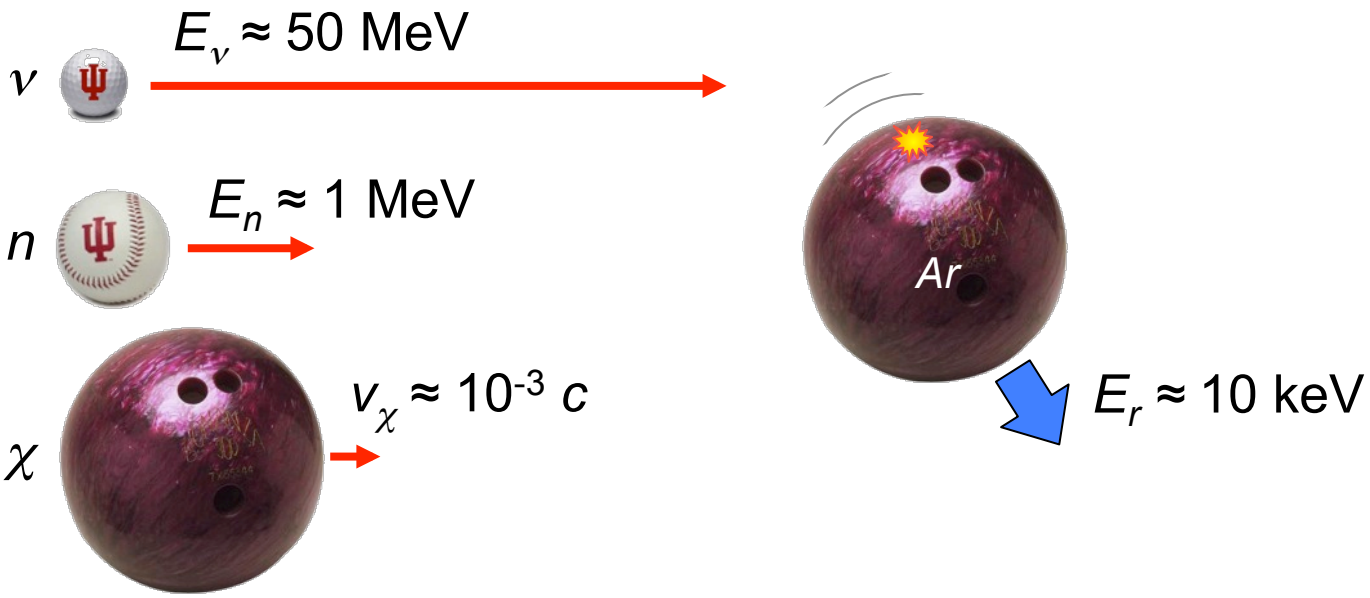


$$E_r^{\max} = \frac{4\mathcal{M}}{(\mathcal{M}+1)^2} E_n \simeq 0.1 E_n$$

where $\mathcal{M} = M/m_n$

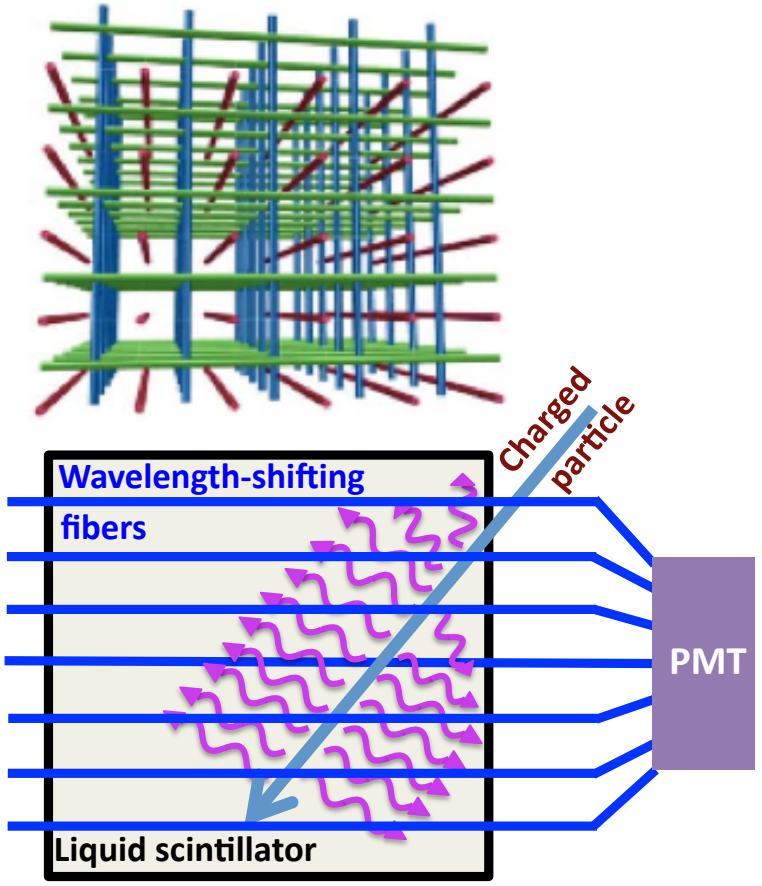
Elastic Scattering Connection: ν, n, χ

- All these particle cause elastic scattering on argon
- Indistinguishable signal → ~10 keV nuclear recoil



SciBath Detector

- 80 L open volume of mineral oil based liquid scintillator
- Neutrons recoil off protons, create scintillation
- 768 wavelength shifting fibers readout
- IU built custom digitizer: 12 bit, 20 MS / s



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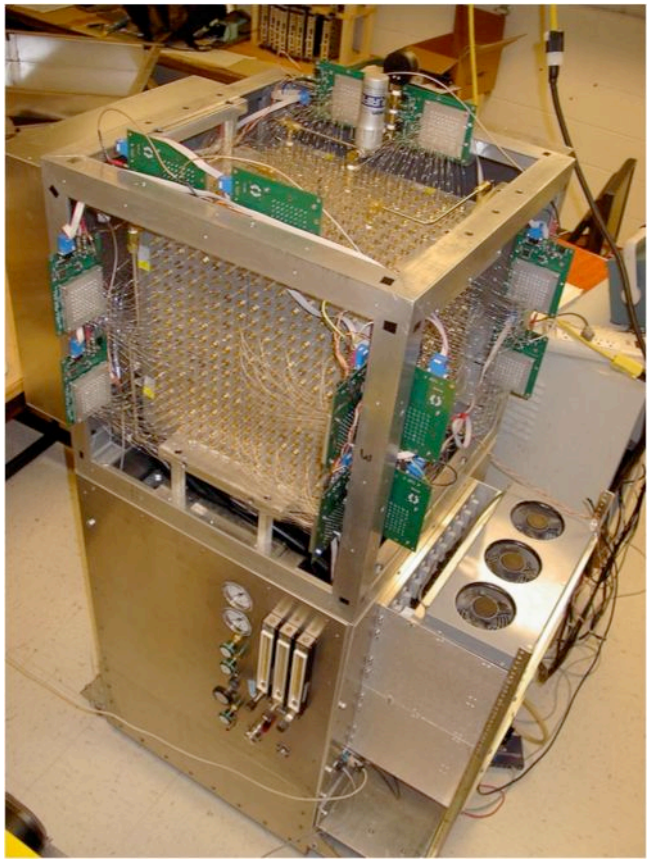

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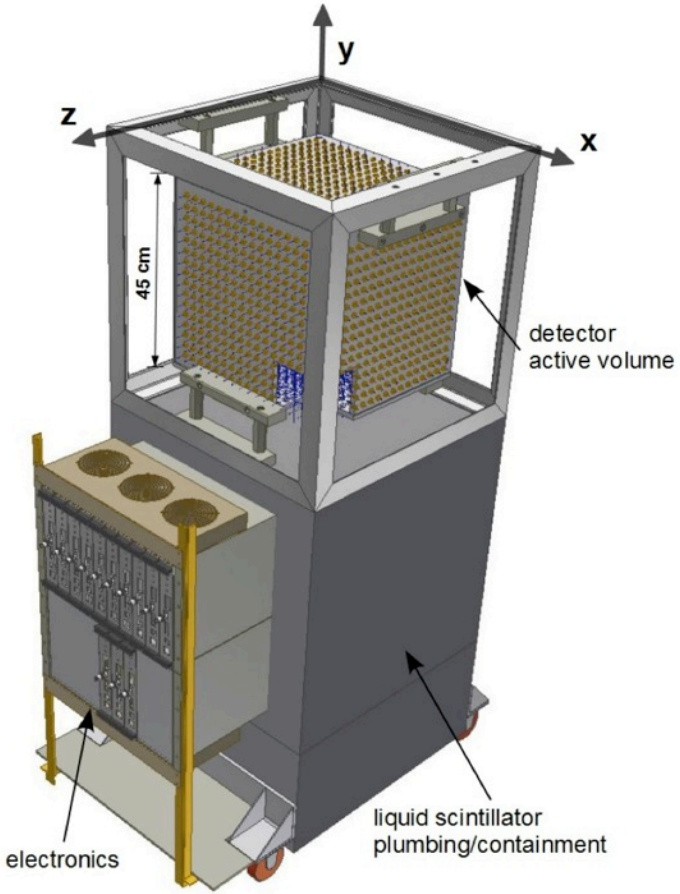
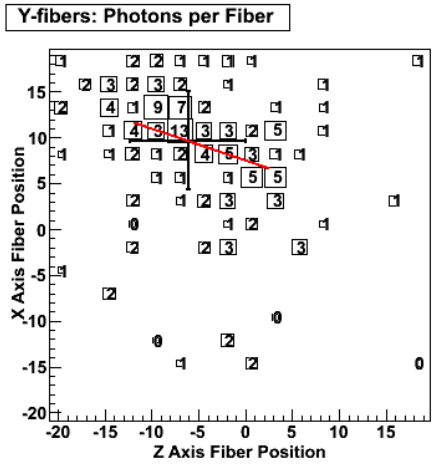
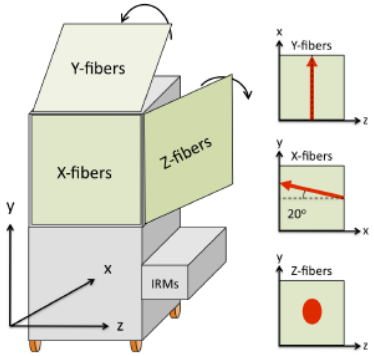
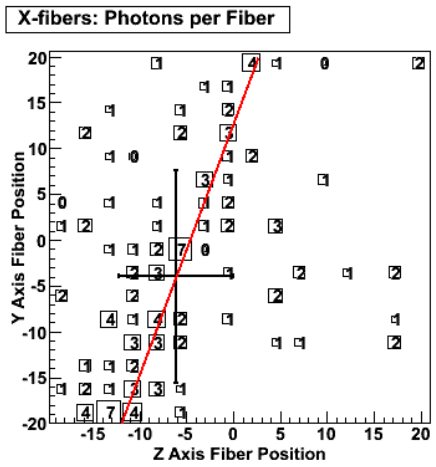


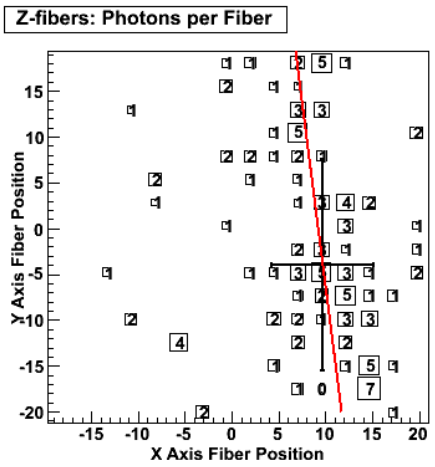
Sample Muon Candidate Event

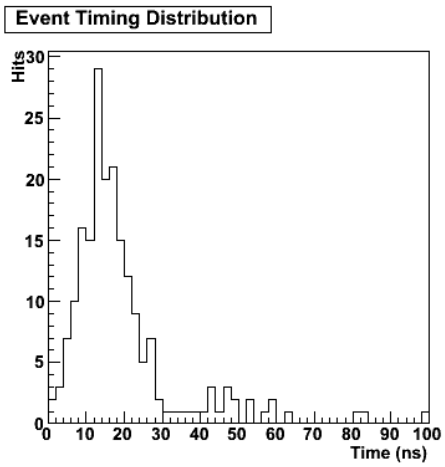




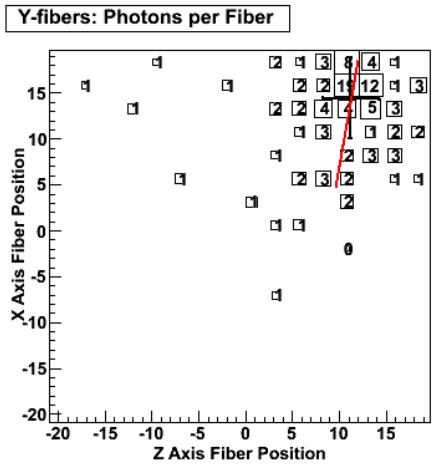
Event Num: 109 (1206)
Multiplicity: 204
Total PEs: 412.6
PEs -- X: 126.0 Y: 158.1 Z: 128.5
PEs^2 -- X: 337.9 Y: 668.8 Z: 360.9
T0: 3.272227153 s
Time to last BIB: 0.0009486 s
$\bar{x}$ = 9.7 ± 5.4 cm -- skew = -1.64 -- kurt = 6.62
$\bar{y}$ = -4.0 ± 11.6 cm -- skew = 0.47 -- kurt = 2.14
$\bar{z}$ = -6.1 ± 6.1 cm -- skew = 0.90 -- kurt = 4.70
$\bar{t}$ = 24.7 ± 36.9 s -- skew = 6.92 -- kurt = 60.43
EigenVals: 196.01, 183.20, 34.72
EigenVect 1: 0.65$\hat{x}$ + -0.19$\hat{y}$ + 0.74$\hat{z}$
EigenVect 2: -0.75$\hat{x}$ + -0.31$\hat{y}$ + 0.58$\hat{z}$
EigenVect 3: 0.12$\hat{x}$ + -0.93$\hat{y}$ + -0.34$\hat{z}$
Point χ^2: 1502.27 Track χ^2: 1496.78
$\bar{d}$ = 6.9 ± 12.7 cm -- skew = -0.41 -- kurt = 2.00
Track length, ellipsoid: 58.69 , rod: 47.70
Spherical radius: 18.57 Eigenvector length: 42.86

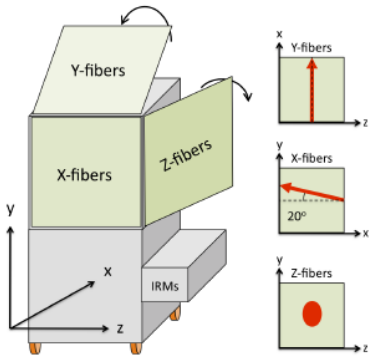




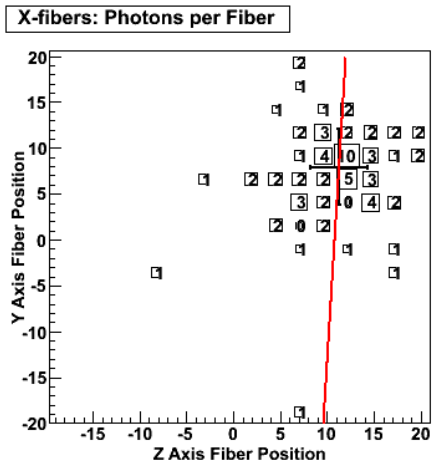


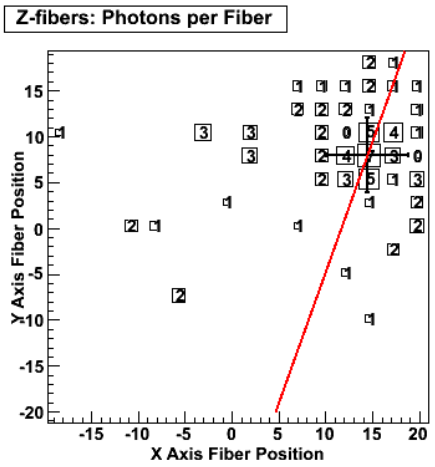
Sample Neutron Candidate Event

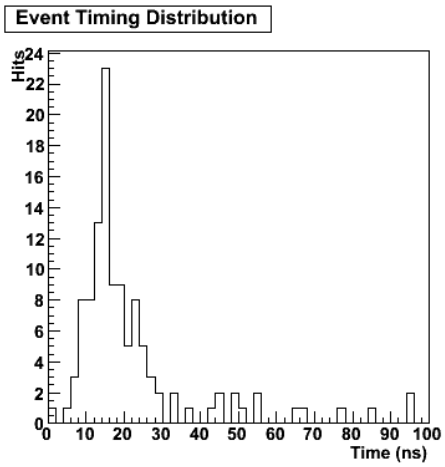




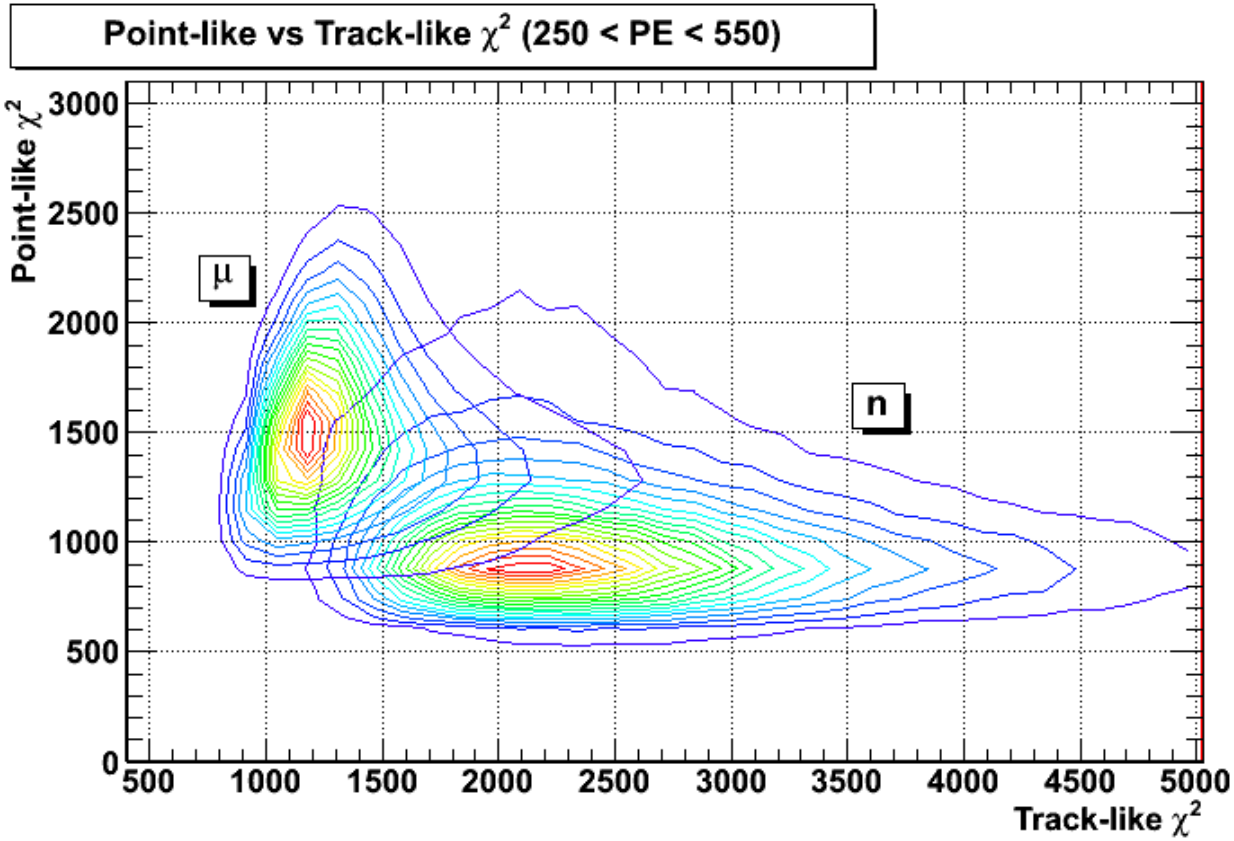
Event Num: 10642 (95796)
Multiplicity: 124
Total PEs: 283.0
PEs -- X: 80.8 Y: 115.8 Z: 86.4
PEs^2 -- X: 282.5 Y: 784.6 Z: 252.9
T0: 92.284587701 s
Time to last BIB: 0.0001213 s
$\bar{x} = 14.4 \pm 4.4$ cm -- skew = -2.92 -- kurt = 13.34
$\bar{y} = 7.9 \pm 4.1$ cm -- skew = -1.55 -- kurt = 10.71
$\bar{z} = 11.3 \pm 3.0$ cm -- skew = -2.21 -- kurt = 17.16
$\bar{t} = 30.6 \pm 43.4$ s -- skew = 5.84 -- kurt = 45.41
EigenVals: 71.20, 30.03, 14.64
EigenVect 1: $-0.03\hat{x} + -0.05\hat{y} + 1.00\hat{z}$
EigenVect 2: $-0.94\hat{x} + 0.33\hat{y} + -0.01\hat{z}$
EigenVect 3: $0.33\hat{x} + 0.94\hat{y} + 0.06\hat{z}$
Point χ^2: 683.47 Track χ^2: 1541.23
$\bar{d} = 12.9 \pm 3.2$ cm -- skew = -5.15 -- kurt = 63.69
Track length, ellipsoid: 29.43 , rod: 24.65
Spherical radius: 9.83 Eigenvector length: 42.42







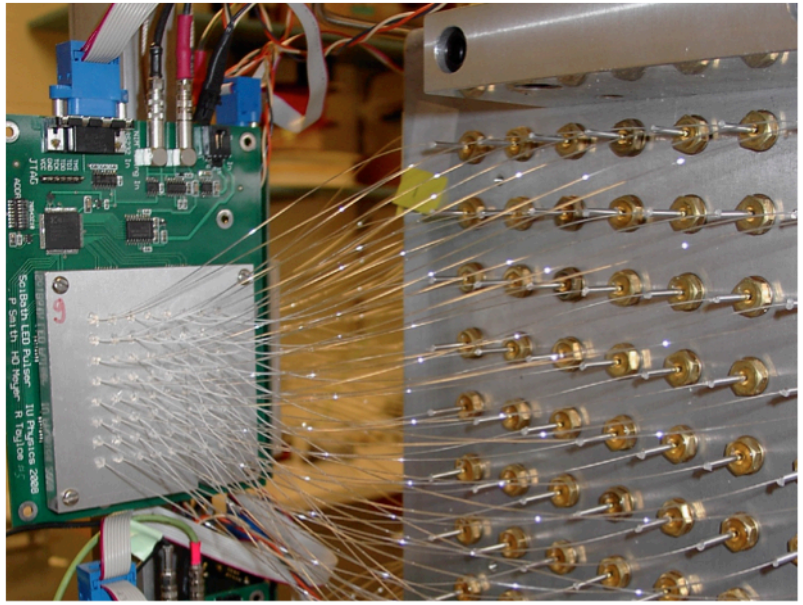
n / μ Particle Discrimination



Calibrating the SciBath Detector

X Energy Deposit (MeV) → **Y** Scintillation Photons Collected → **Z** Signal Voltage (ADCs)

- Low-light LED pulser (**Y→Z**)
- Use cosmic rays with known energy deposit (**X→Y**) requires previous calibration to count photons
- Detect 6 PEs / MeV
  → want to improve



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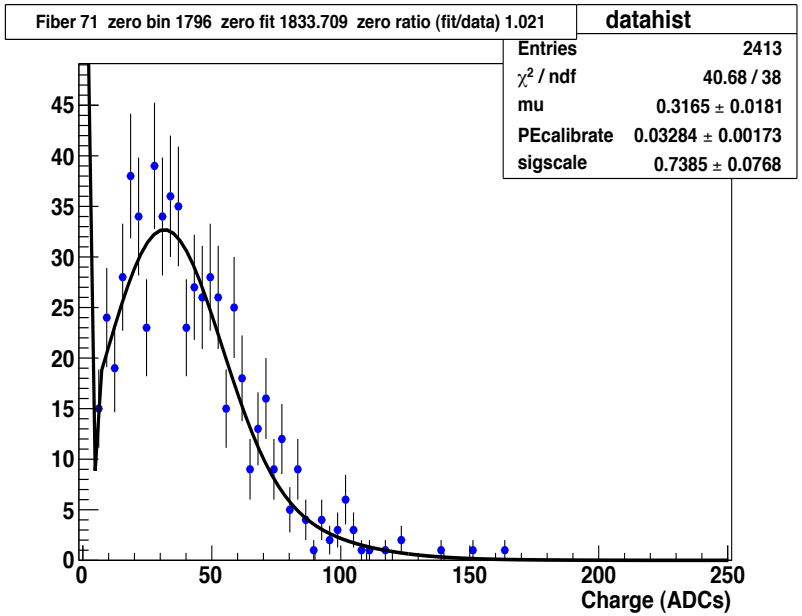
Single-PE LED Calibration



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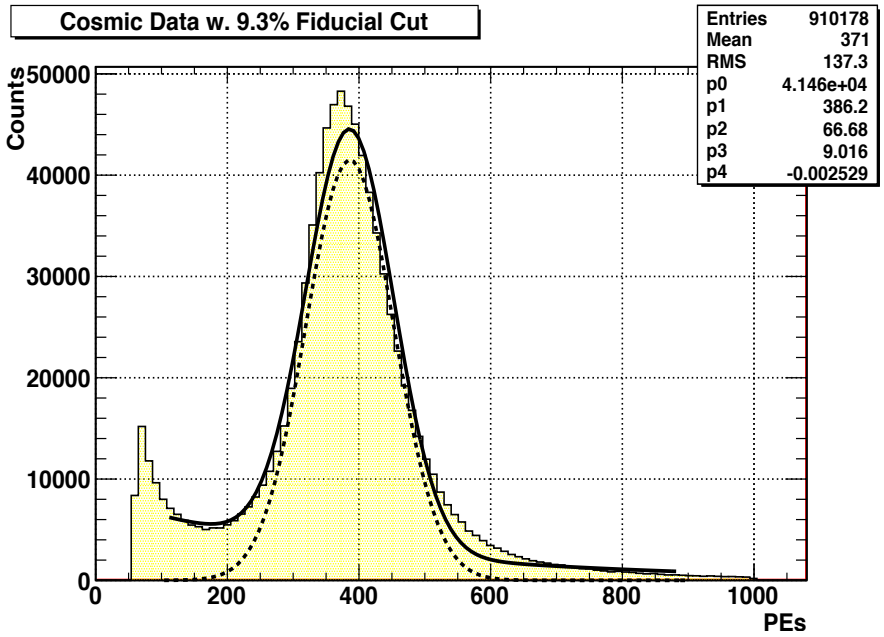
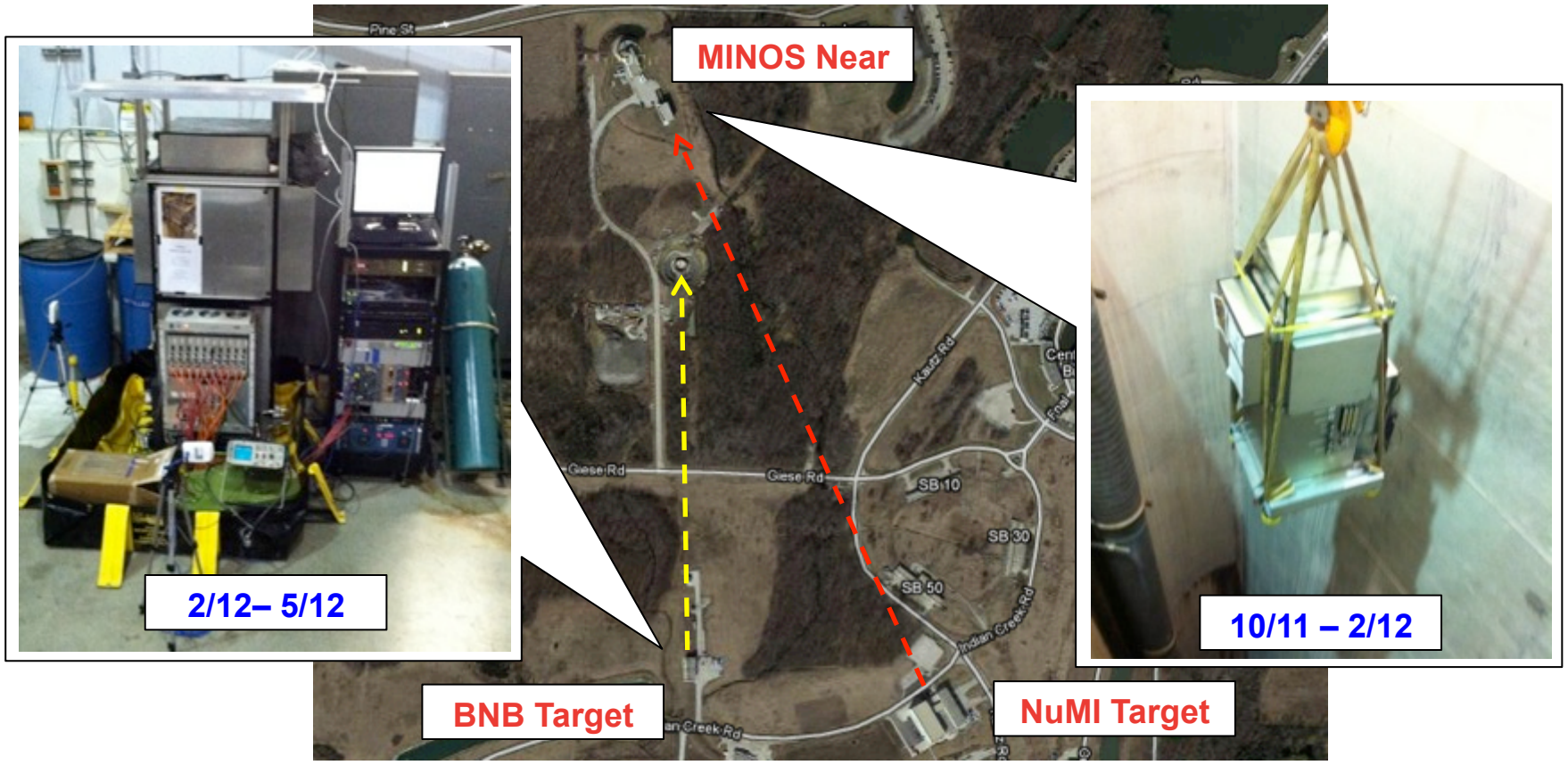
MIP Cosmic Ray Calibration Peak

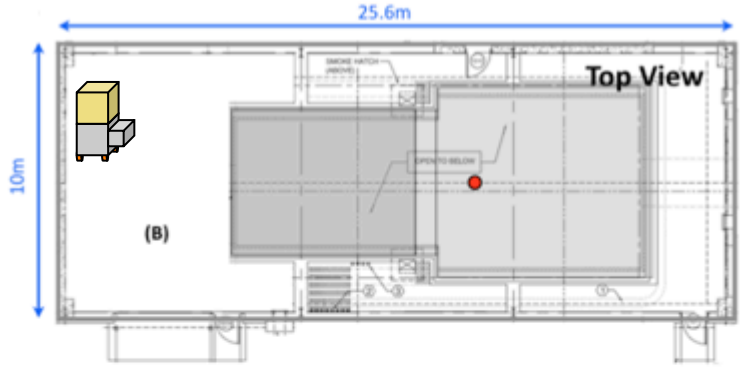


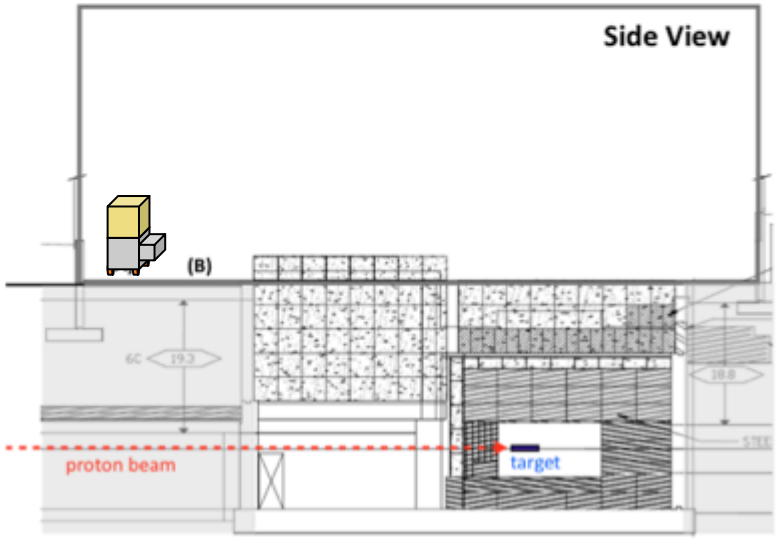
Fermilab Measurement Sites



MI-12 Neutron Background Run

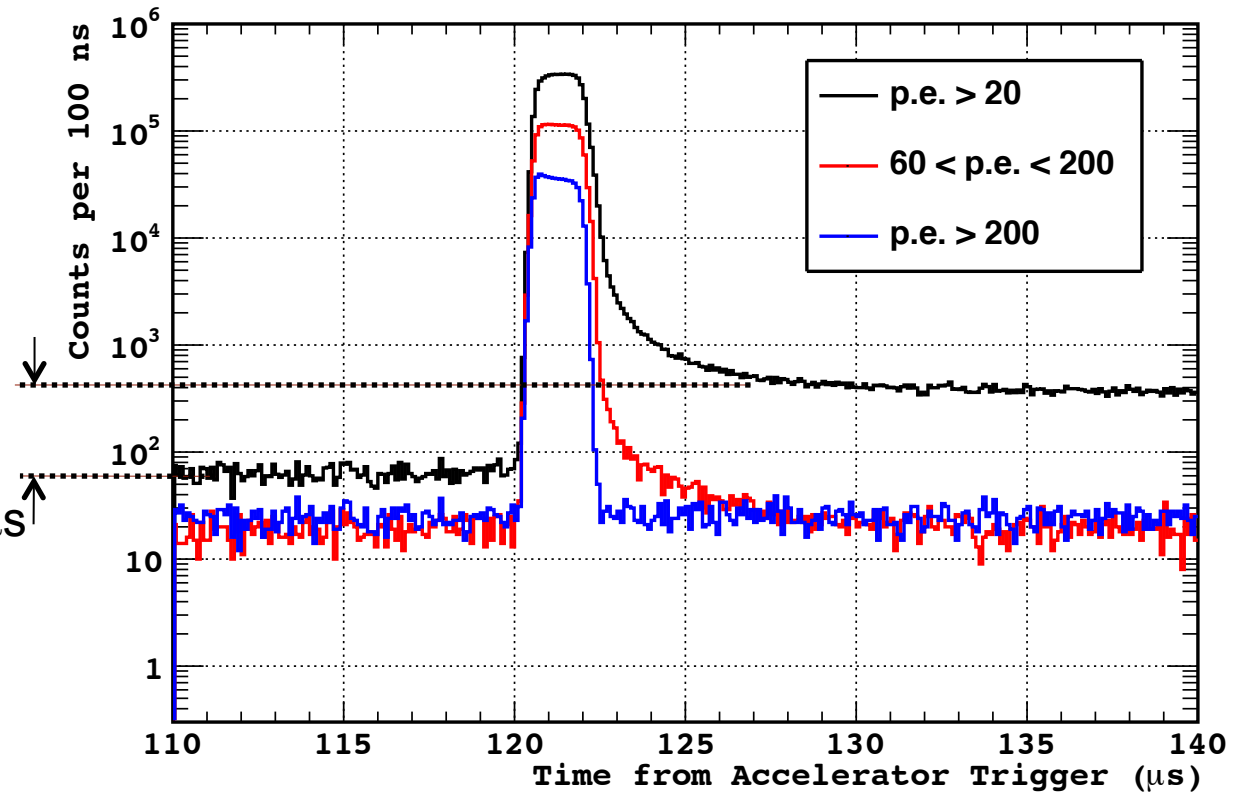
- Neutron flux ~20 m from target
- In-line behind beam target (ground)
- 29 Feb. – 23 Apr., 2012
- 4.9×10^{19} total protons on target (POT)
  (4.5×10^{12} per pulse)





MI-12 Beam Time Per PE "Group"

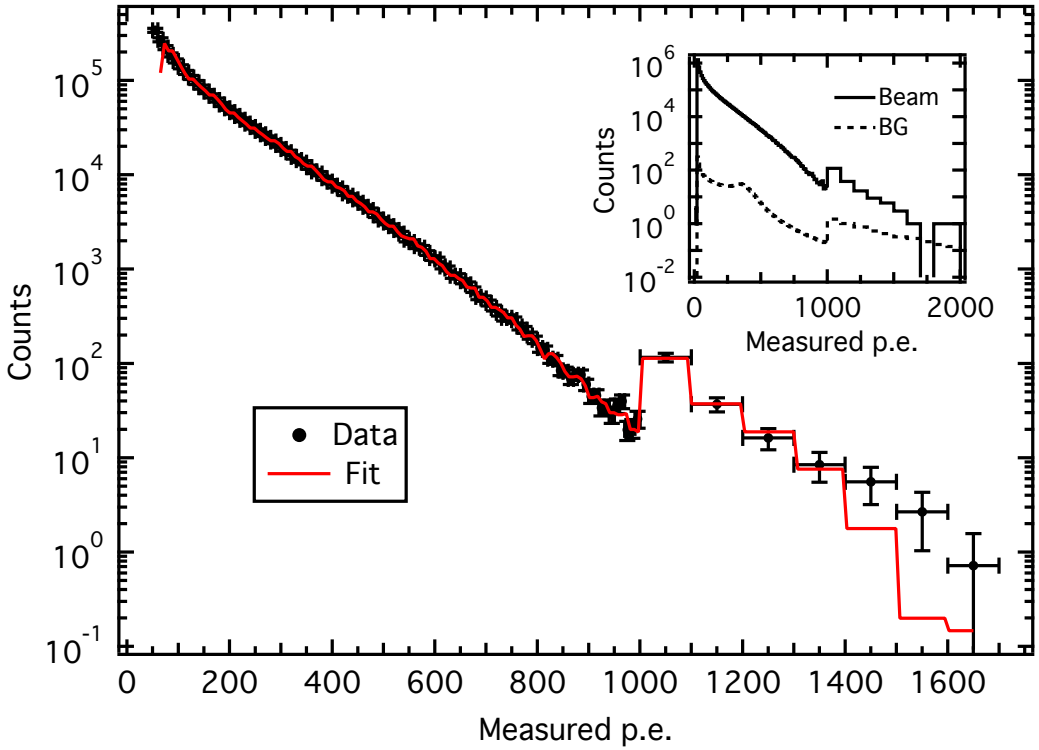
- **HIGH PE** group shows beam time structure
- **MEDIUM PE** group has few-μs excess – slower neutrons arriving later
- **LOWEST PE** group has significant excess – 200 μs lifetime from *n*(*p*, *d*)γ neutron capture reaction



BNB Neutron Energy Spectrum

- E_n unfolded from PEs spectrum simulation of detector response
- 2.44 ± 0.34 pulse^{-1} m^{-2} (E_n > 40 MeV)
- Lose sensitivity > 200 MeV;
- Neutron spectrum 20 m from BNB

Raw PE Spectrum In-Beam



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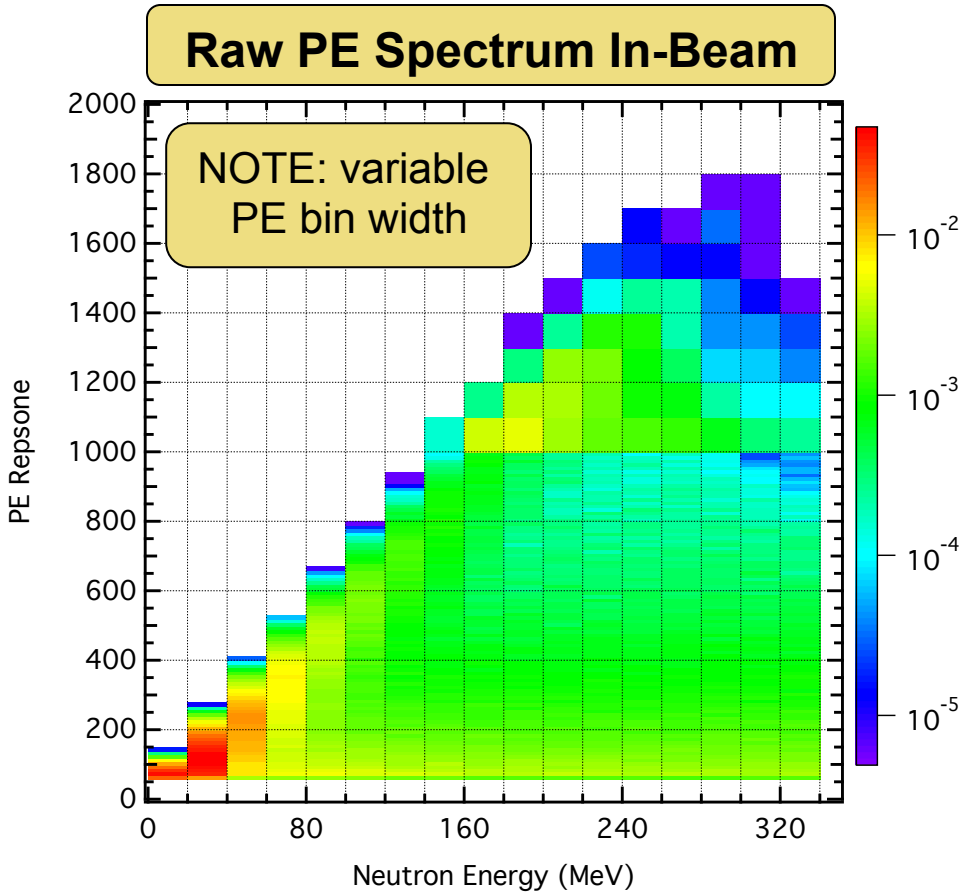

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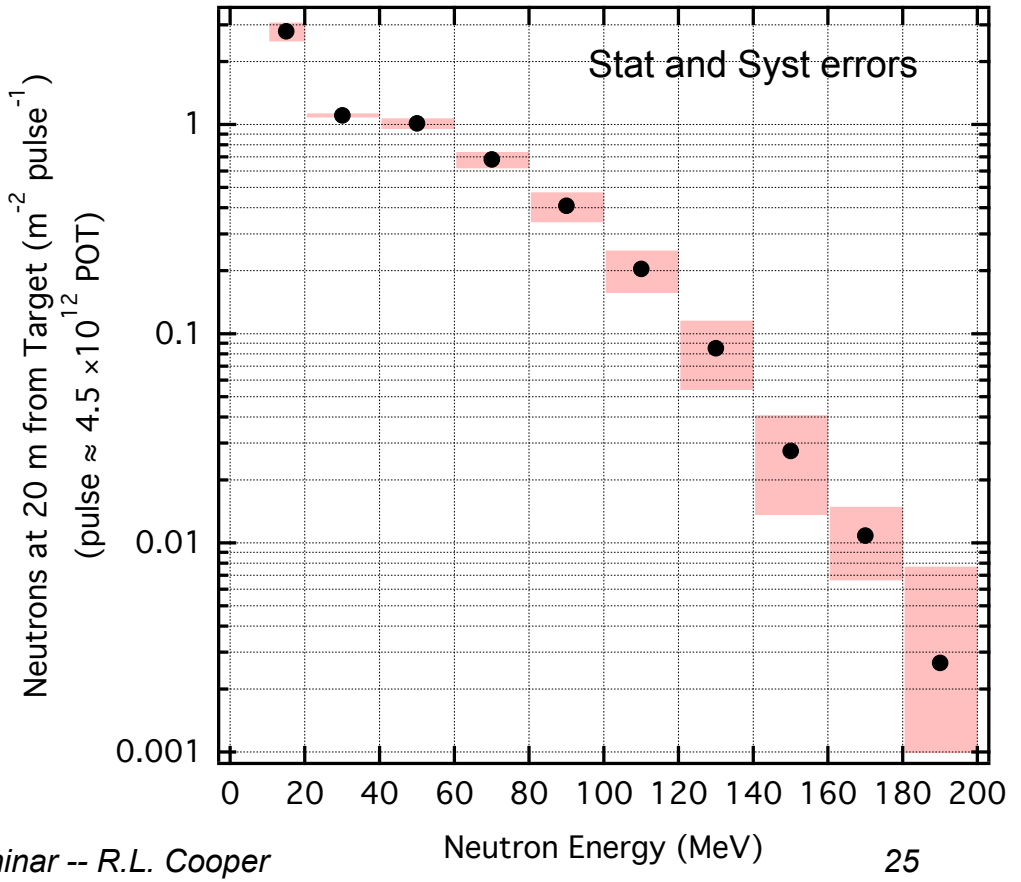
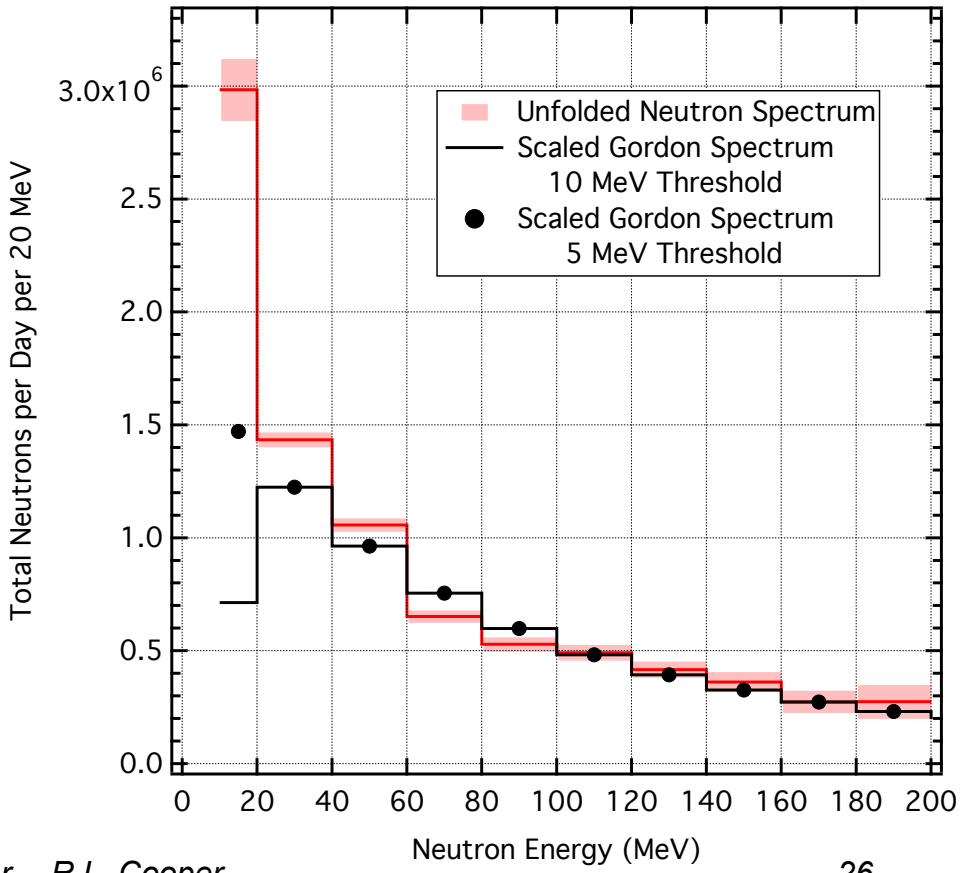
Unfolded Neutron Energy Spectrum



Validation of Unfolding Techniques

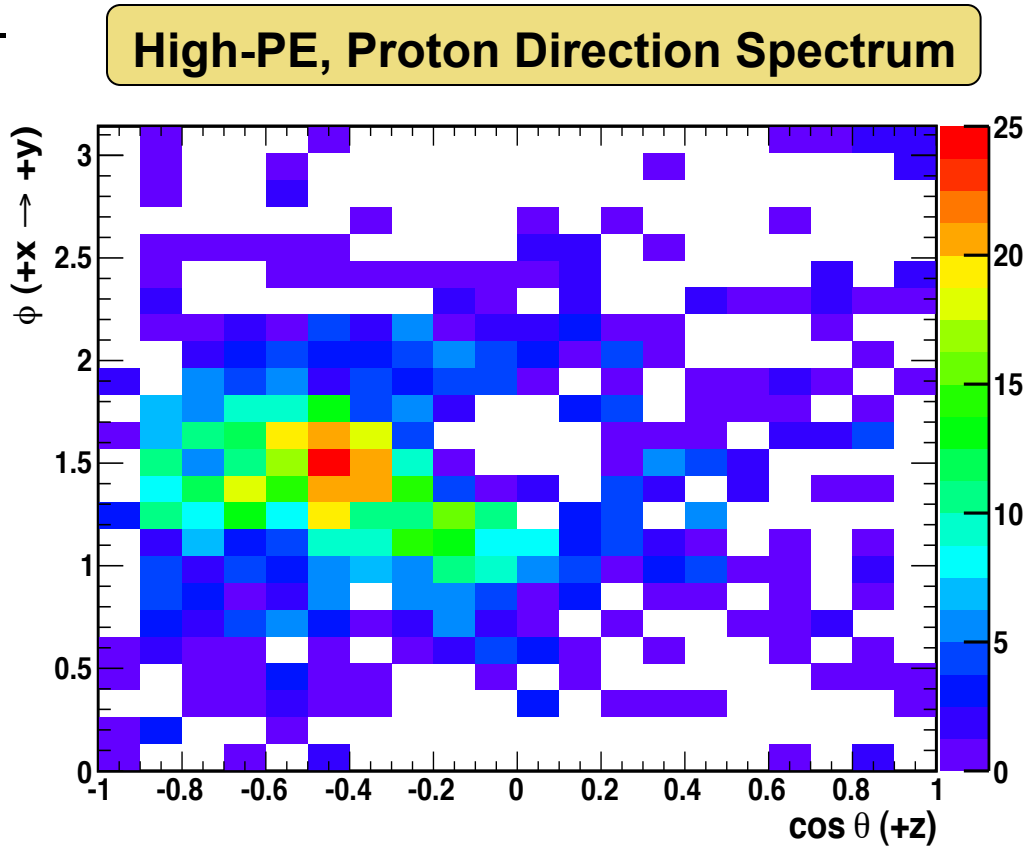
- Cosmic ray neutron spectrum also unfolded
- Gordon et al., IEEE TNS **51**, (2004) 3427 parameterizes surface neutron flux from Bonner sphere data
- Energy shape matches, overall scale factor needed

Unfolded Cosmic Neutron Spectrum



Direction Spectrum

- High PE protons will be track-like; can be imaged
- Principle component analysis yields eigenvector
- Back-projecting direction spectrum tends to point upstream of target
- Tracking validated with cosmic rays and NuMI beam



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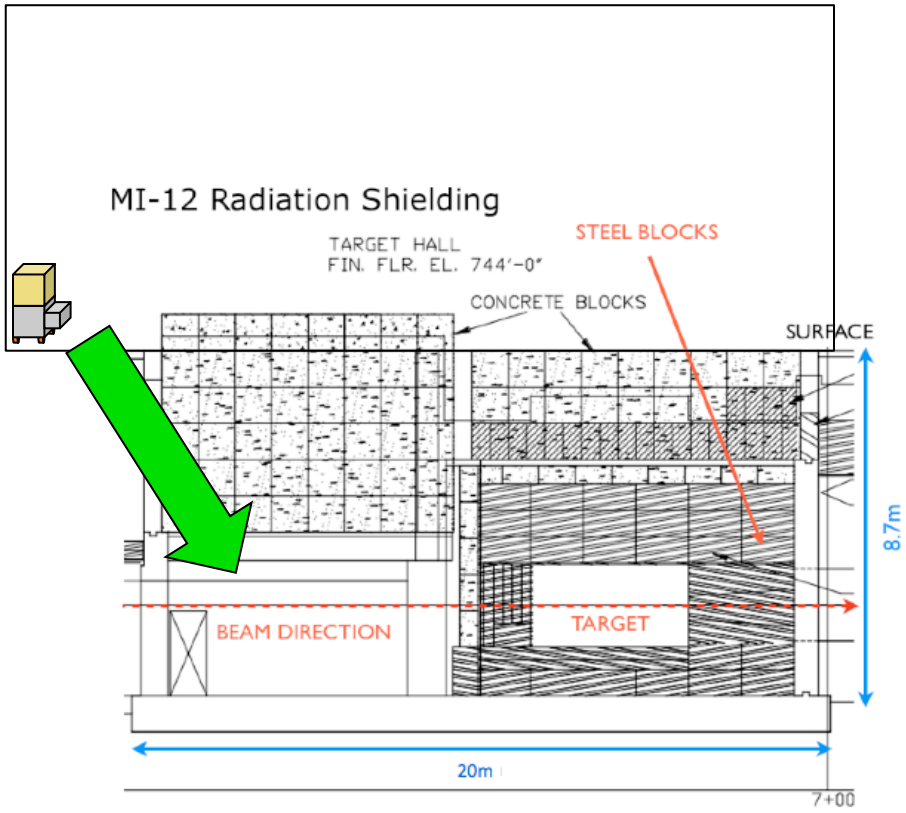
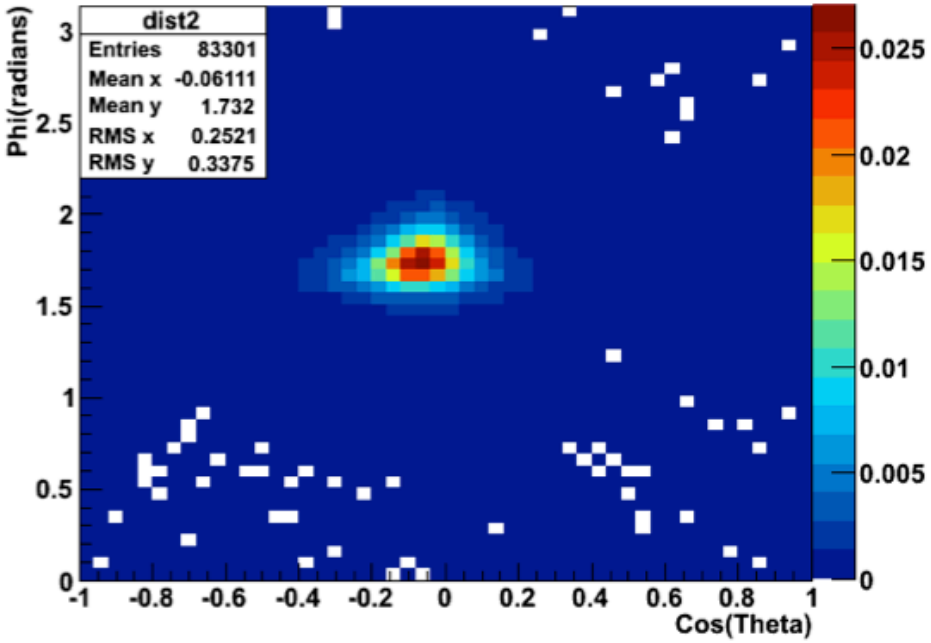


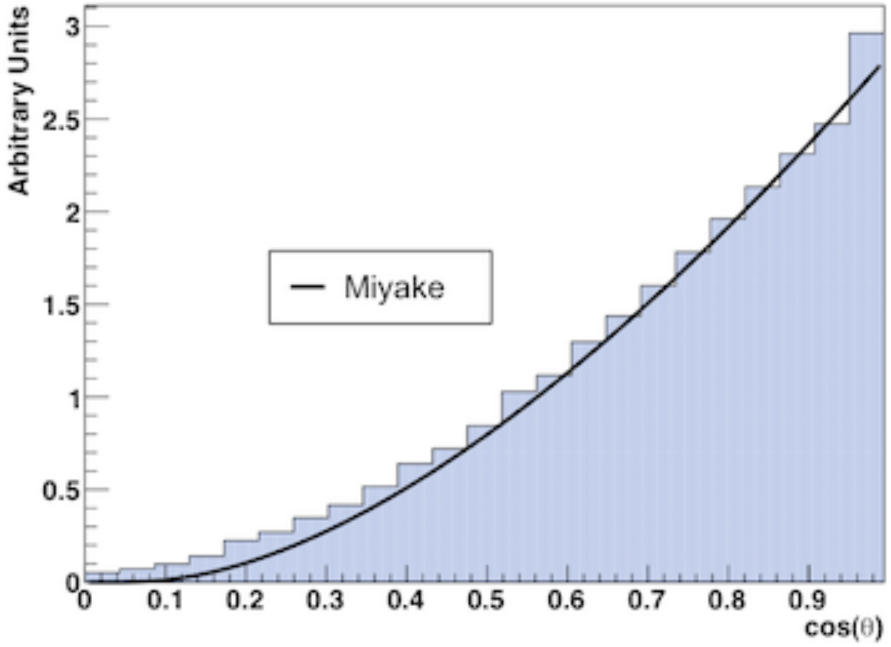
Validation of SciBath Tracking

- Tracking algorithms validated with NuMI underground data

NuMI Near Beam Muons



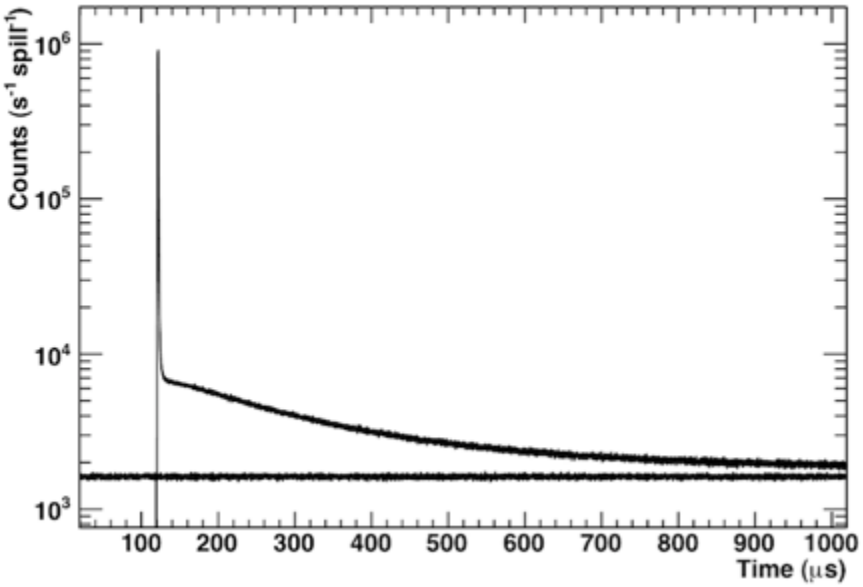
NuMI Near Cosmic Ray Muons



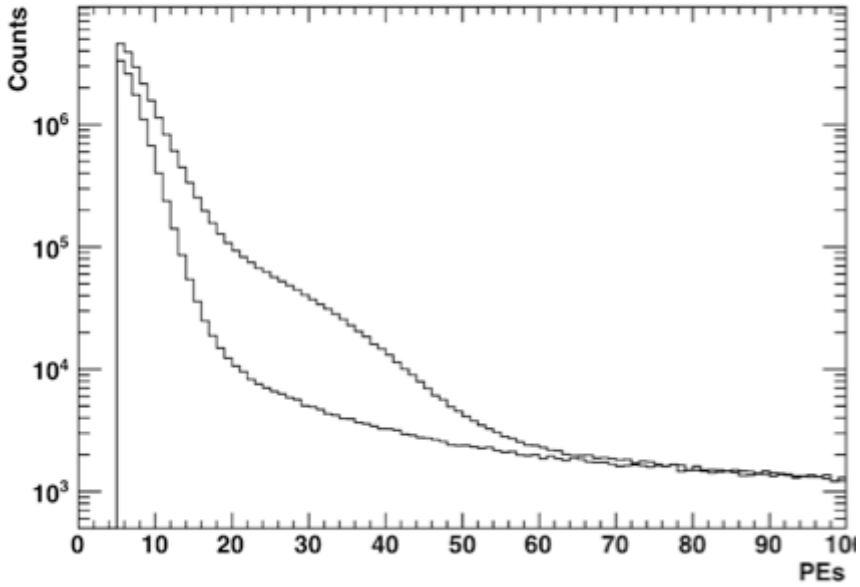
Capture-Gated Neutrons at MI-12

- At surface, accidental rate (and high primary rate) precludes $n(p,d)\gamma$ capture gating → clear statistical sensitivity to thermal captures

MI-12 After-Beam Timing Spectrum



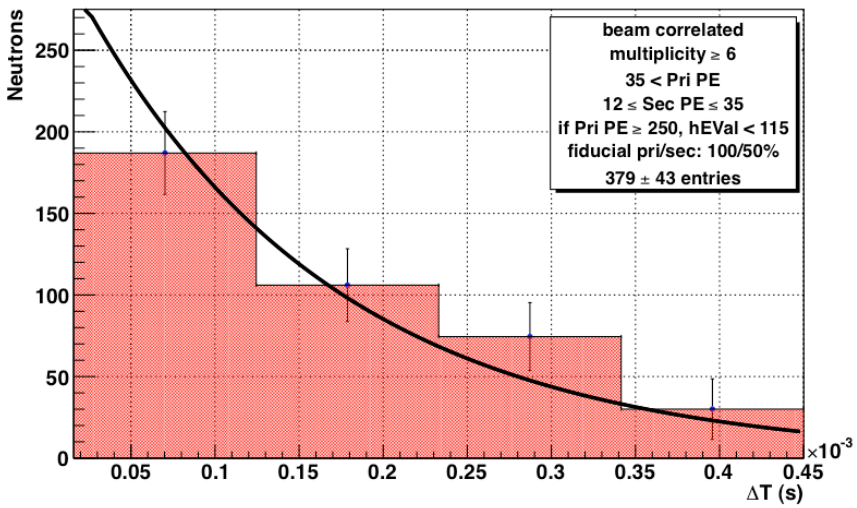
MI-12 After-Beam PE Spectrum



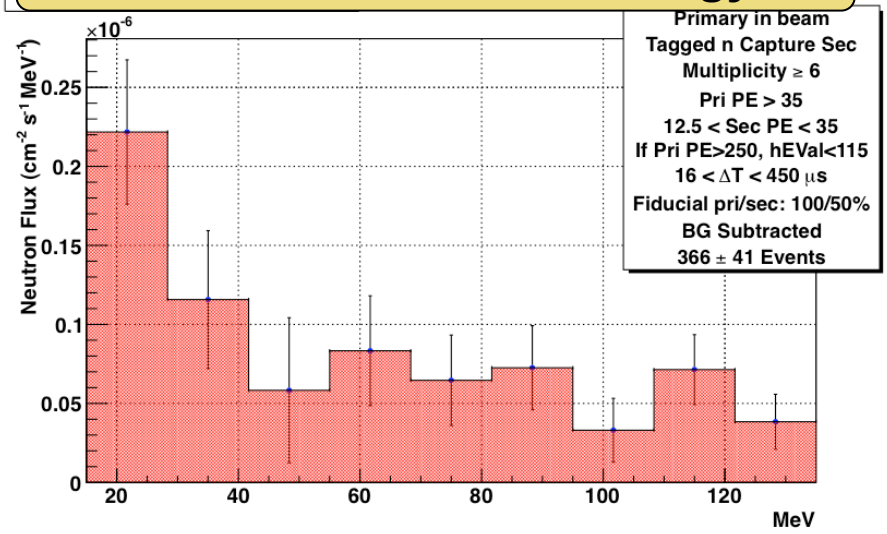
Capture-Gated Neutrons at NuMI

- NuMI near hall (100 m overburden) capture-gating neutron spectroscopy technique demonstrated (L. Garrison thesis)

NuMI Beam Neutron Capture Timing



NuMI Beam Neutron Energy



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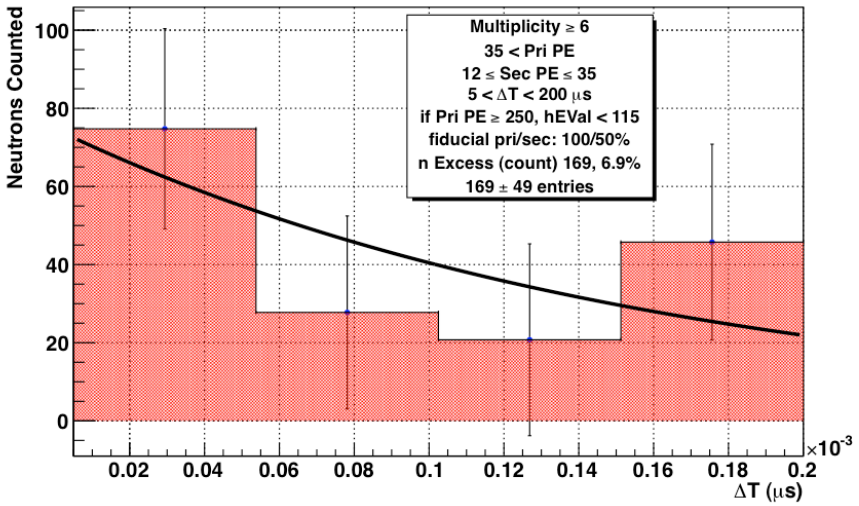
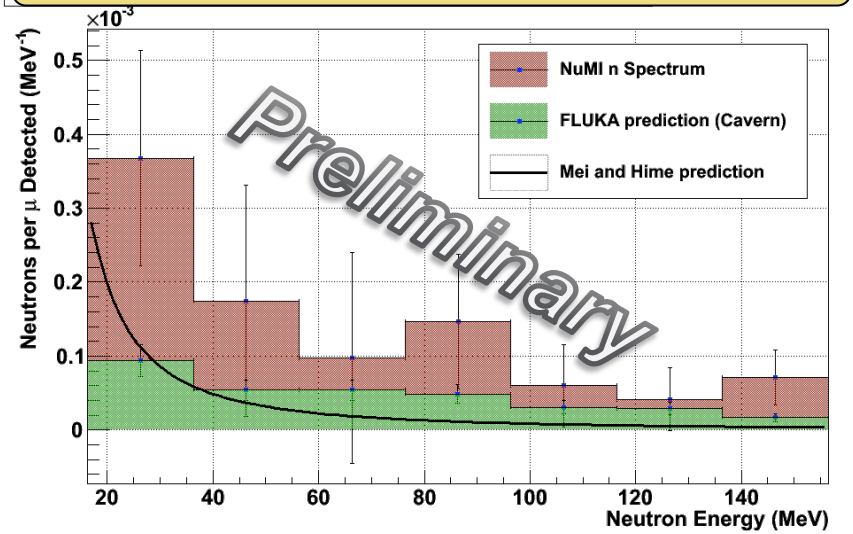
NuMI Cosmic Neutron Capture Timing

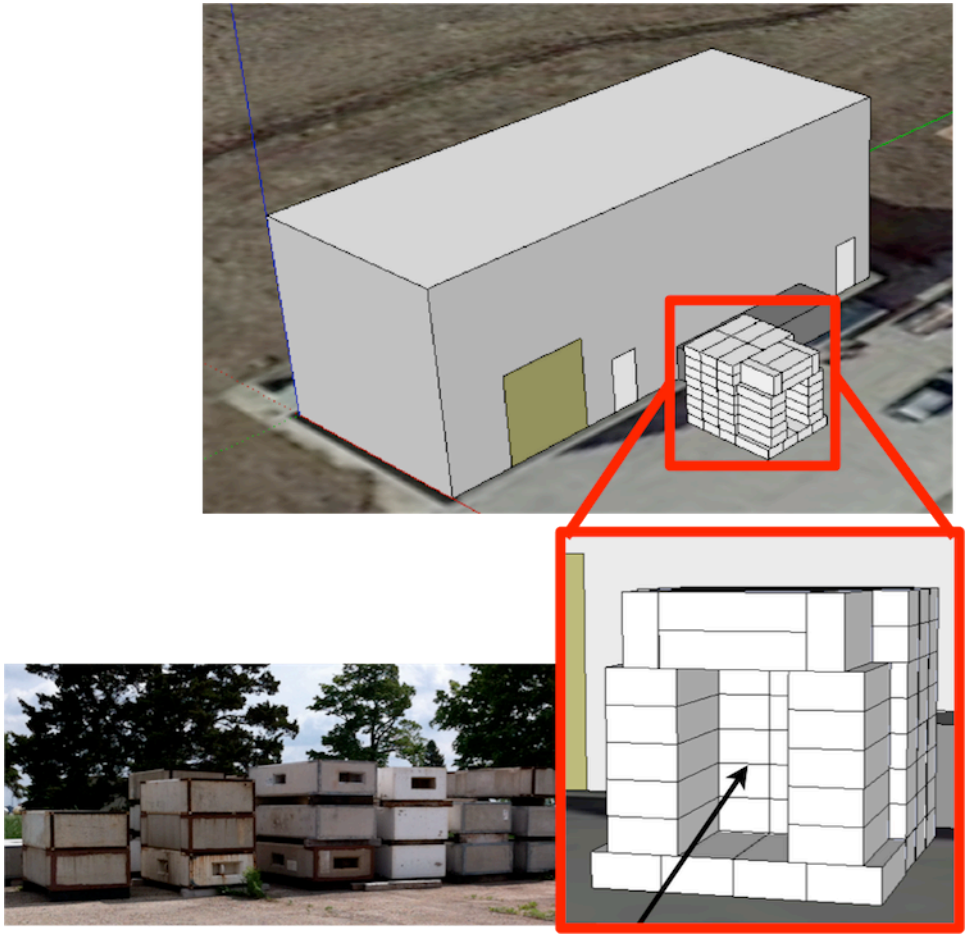


NuMI Cosmic Neutron Energy



Current Studies

- 2012 measurements at one position with no shielding
- We are improving SciBath, building concrete shielding
- Locate a viable location for CENNS & CAPTAIN
- Survey the area with portable detector



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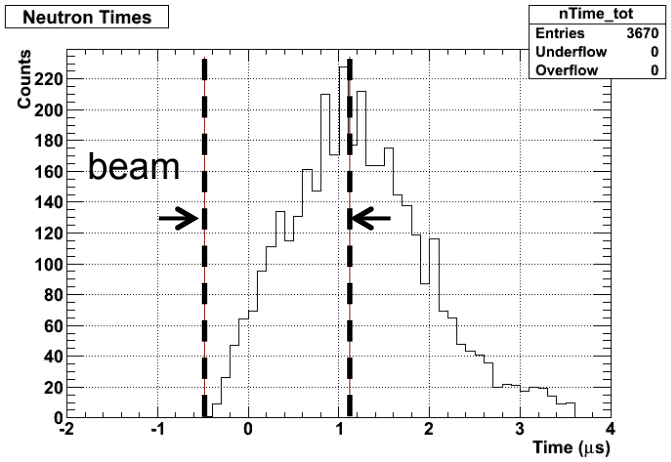
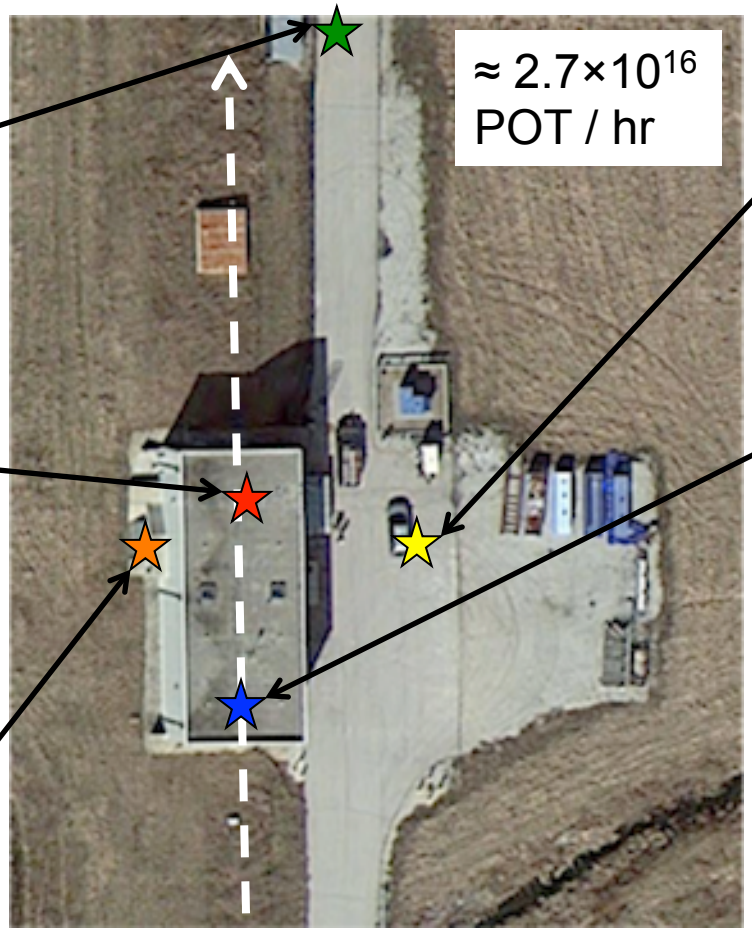


Beam Off-Target Rates (> 0.5 MeV)

50 m Absorber
- 6 m from Fe beam stop
- 310 n / 10^{16} POT

Collimator
- 8 m from Be beam target
- 5608 n / 10^{16} POT

Stairwell
- 9 m from Be beam target
- 1384 n / 10^{16} POT



Target 90° FOX
- 20 m from Be beam target
- 390 n / 10^{16} POT

2012 SciBath Loc
- 20 m from Be beam target
- 211 n / 10^{16} POT

Neutron spectrum unfolding underway

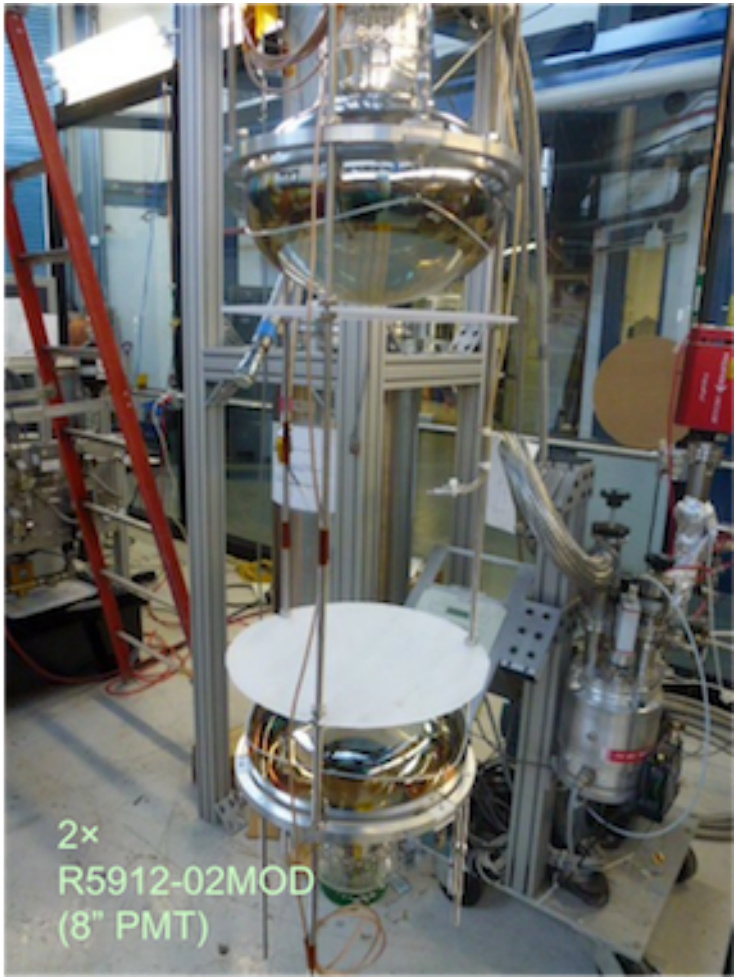
CENNS-10

Goals

- Develop LAr technology
- Perform very high-energy neutron calibrations

Status

- Moved to Indiana
- Planning for calibration at Los Alamos WNR neutron beam



CENNS-10

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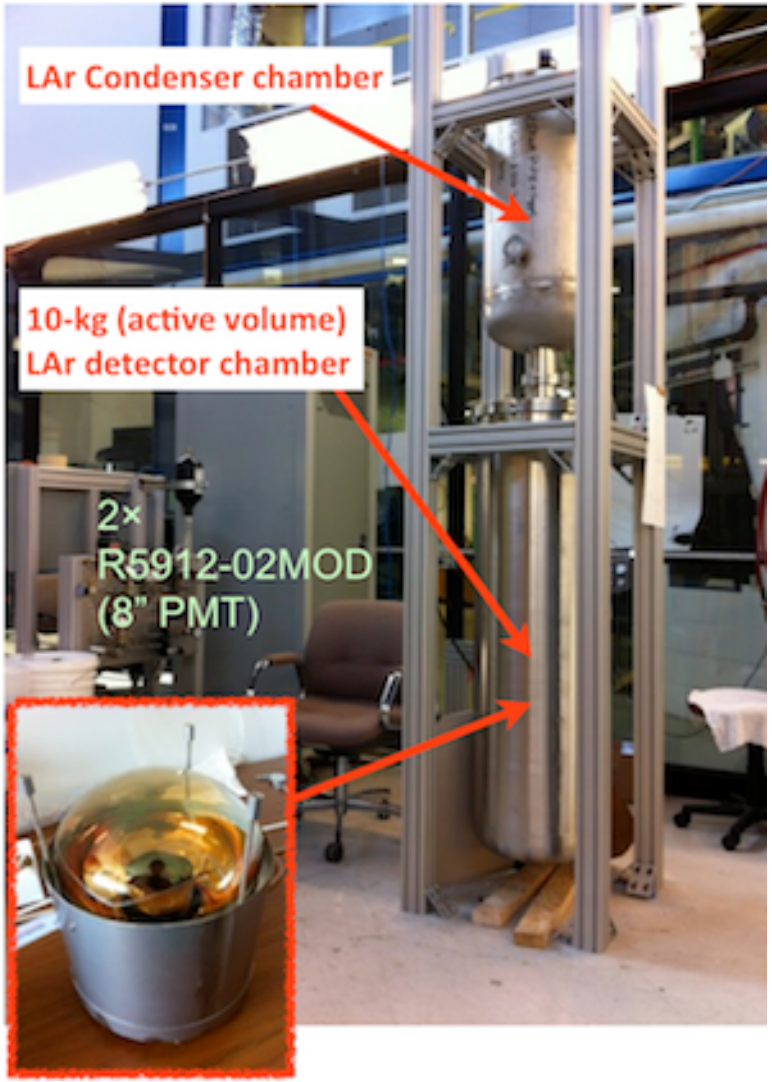
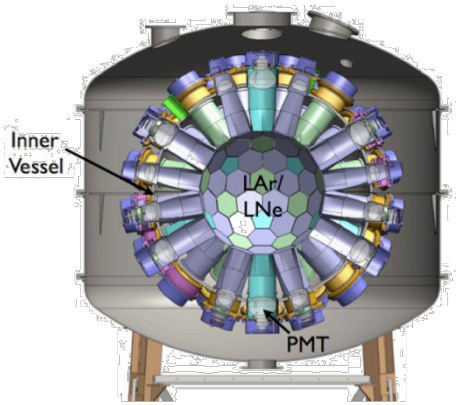


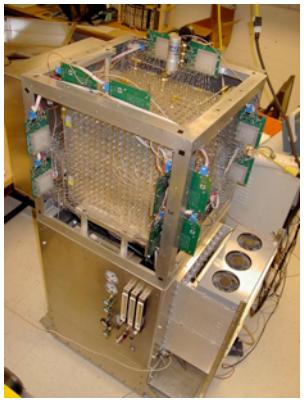
Summary of BNB Work for CENNS



MiniCLEAN
First CENNS measurement

SciBath
Fast neutron measurements (10-200 MeV)

Neutrons backgrounds



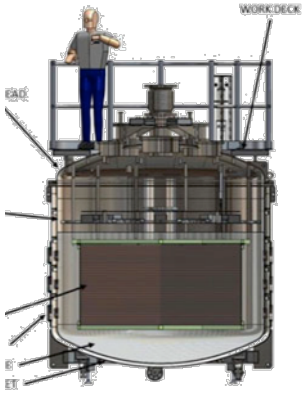
LAr hardware testing

EJ-301 Cells
Portable array (0.5-20 MeV)

preparatory measurements

CENNS-10
10 kg LAr testing prototype

CAPTAIN
Low-E neutrino cross sections



Summer 2015 Plans

- **BNB**: Plan to measure near BNB target building for CENNS, CAPTAIN, and general SBN program
  (May *or* June for 1 month)

- **SciBooNE**: Measure high-energy neutrino-induced neutrons and constrain thermal neutron rates from $n(p,d)\gamma$ capture rates:

  relevant for ANNIE, microBooNE, and SBN (May *or* June for 1 month)

BACKUPS

Structure of the CENNS Signal

- Predicted scattering rate

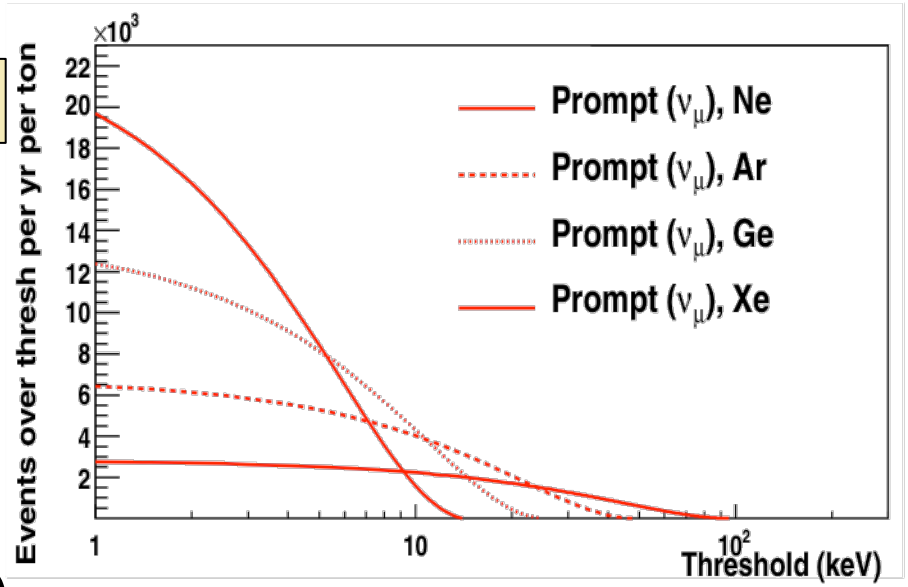
$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}\left[(1-4\sin^2\theta_w)Z - N\right]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)F(Q^2)^2$$

Detection Rate [ton^{-1} year^{-1}]

≈ 0 → protons have little influence

square of sum → part of coherence condition

nuclear form factor → distribution of neutrons

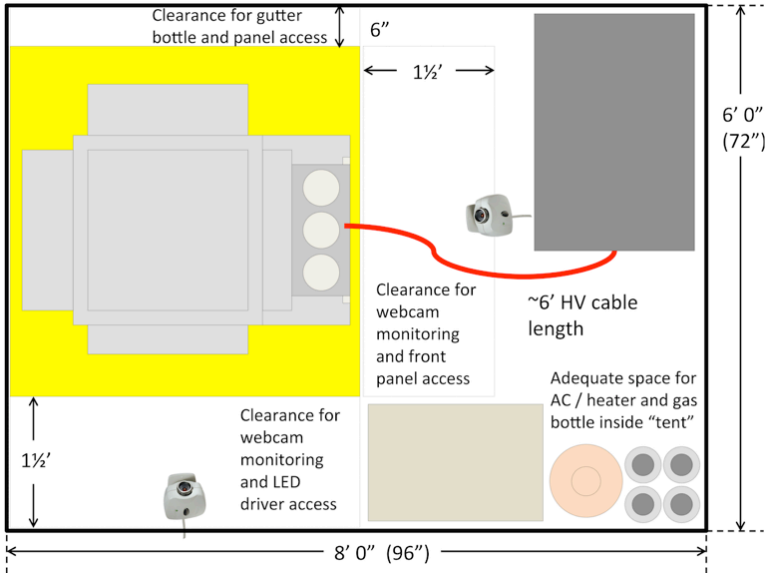


- Recoil energy (M^{-1}) and rate (N^2)

MI-12 Neutron Background Run

- Neutron flux ~20 m from target
- In-line behind beam target (ground)
- 29 Feb. – 23 Apr., 2012
- 4.9×10^{19} total protons on target (POT)
  (4.5×10^{12} per pulse)

Utility Trailer for BNB Measurement



CENNS-10 On the Move

Off-Target Runs